

Experimental Analysis of Unburned Hydrocarbon Emissions in Lean-Burn Spark-Ignition Engines

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Lean-burn spark-ignition engines are widely recognized as an effective approach for improving thermal efficiency and reducing CO₂ emissions. However, their practical application is constrained by increased unburned hydrocarbon (UHC) emissions, which arise from incomplete combustion, flame quenching near chamber walls, and cycle-to-cycle variations in flame development. These issues become more pronounced as the mixture becomes leaner, making it essential to clarify the dominant mechanisms of UHC formation under lean conditions. Ethanol, a renewable biofuel with high laminar flame speed, strong resistance to knock, and favorable vaporization characteristics, has the potential to enhance combustion stability near the lean limit. This study experimentally investigates how ethanol blending influences combustion stability, UHC formation pathways, and overall THC emissions in lean-burn operation.

A single-cylinder research engine, derived from a commercial 4-cylinder gasoline engine, was used to isolate and analyze combustion behavior under controlled conditions. Fast-response FID (0.8 ms) and NDIR (8 ms) sensors were installed upstream of the exhaust manifold to obtain crank-angle-resolved THC, CO, and CO₂ concentrations. FTIR analysis was conducted downstream to characterize THC species under steady-state operation. Four fuels—E0, E20, E50, and E100—were tested at IMEP = 1 MPa and λ ranging from 1.03 to 1.75. In-cylinder heat flux sensors were employed to evaluate wall quenching behavior and estimate quenching distance using the thermal formulation proposed by Boust et al., allowing simultaneous assessment of flame-wall interaction and bulk combustion completeness. This combination of high-speed gas analysis and heat flux measurement enabled detailed tracking of both global combustion behavior and localized quenching phenomena.

Across all fuels, THC emissions increased with leaner mixtures. Detailed cycle-resolved analysis revealed that cycles exhibiting low cumulative heat release produced significantly higher CO and THC emissions. These cycles, defined as Bulk Quench Cycles (heat release $\leq -5\%$ of the cycle average), occurred frequently under lean conditions with E0 due to unstable flame propagation, partial burn, and increased sensitivity to mixture inhomogeneity. Ethanol blending suppressed cycle-to-cycle variation in heat release, reduced the occurrence of Bulk Quench Cycles, and consequently lowered THC emissions. This improvement is attributed to ethanol's higher laminar flame speed, enhanced vaporization characteristics, and improved mixture preparation, all of which contribute to stabilizing lean combustion and reducing the likelihood of partial burn events. The results clearly demonstrate that ethanol's combustion-enhancing properties directly mitigate the dominant source of UHC under lean operation.

Wall quenching behavior was also examined. Although quenching distance typically increases with air–fuel ratio due to reduced flame temperature and slower flame propagation, the present engine exhibited nearly constant quenching distance across lean conditions. This is because lean operation simultaneously increased in-cylinder pressure, which counteracted the dilution effect and reduced the quenching distance predicted by the thermal model. After removing pressure dependence, the quenching distance showed the expected increase with λ . However, the estimated UHC mass trapped in the wall quenching layer contributed only marginally to total THC emissions compared with Bulk Quench Cycles, indicating that wall quenching is not the dominant factor governing UHC formation under the tested conditions. This finding highlights the importance of focusing on bulk combustion completeness rather than solely on flame-wall interaction when optimizing lean-burn strategies.

Overall, these findings demonstrate that incomplete combustion caused by Bulk Quench Cycles is the dominant source of UHC under lean-burn operation, while wall quenching plays a secondary role. Ethanol blending effectively improves combustion stability, suppresses incomplete-combustion cycles, and reduces UHC emissions, highlighting its potential as a practical strategy for achieving cleaner and more efficient lean-burn SI engine operation. The results provide valuable insights for optimizing future biofuel utilization, improving lean-burn calibration strategies, and advancing high-efficiency engine technologies aimed at carbon-neutral mobility. Furthermore, the experimental framework established in this study offers a robust methodology for future investigations into flame quenching, mixture preparation, and combustion stability in next-generation SI engines.

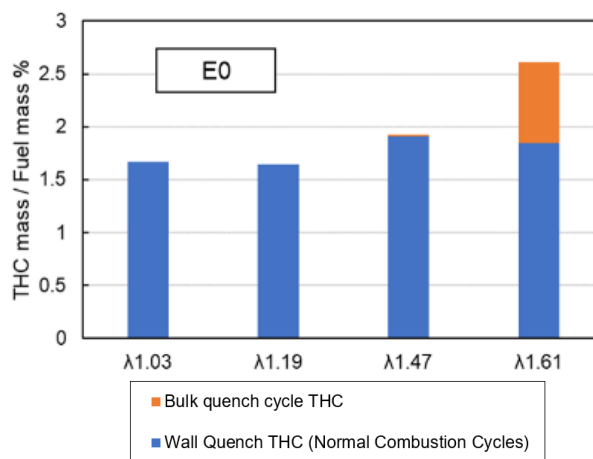


Fig.1 The contribution to THC (E0)